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ELECTROMECHANICAL PULSERS

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FOREWORD

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ABSTRACT

Considered is the feasibility of generation of high energy pulses directly by electromechanical power conversion. without relying on intermediate storage in electrical form. Extremely large values of power output per unit volume of the machine can be obtained. within the ambit of present day technology. when the materials are pushed to the limit set by tensile strength. As an example. units having overall dimensions comparable with those of a medium sized turbo-generator can be built to deliver energies up to 10^{10} Joules in one second and 10^{8} Joules in a few milliseconds. Guiding principles for the design of these generators are presented. General relations governing the performance of converters employing hot plasmas are established.

PUBLICATION REVIEW

This report has been reviewed and is approved. For further technical information on this project. contact William C. Quinn. EMATP. X75141.

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ELECTROMECHANICAL PULSERS

1. GENERAL PRINCIPLES

An electromechanical pulser[1, 2, 3] is a device designed to transfer a high energy pulse into an electrical load by direct electromechanical power conversion, without relying on intermediate storage stages. This is in contrast with conventional pulse modulating techniques which require at least one stage of energy storage in electrical form, with consequent increase in bulk and loss in efficiency and reliability. The physical realization of an electromechanical pulser can take such a variety of forms that it is difficult, at first, to evaluate their relative merits and ultimate capabilities. We shall, therefore, start here by establishing some general relations, and later proceed to discuss the performance characteristics of specific pulsers.

Of interest are pulse energies up to 10^{10} Joules and pulse widths ranging from one millisecond to a second. For an appreciation of the energies involved we tabulate the volume required for storage in the various forms, as follows:

Energy form	Chemical	Heat	Kinetic	Magnetic	Electric
Storage element	Fuel	Latent heat of fusion (steel)	Flywheel	Inductance	Capacitor
Volume in m^3	1	10	10^3	10^4	10^6

The corresponding pulse power requirements, when evaluated on the basis of one millisecond pulse width, are larger by at least three orders of magnitude than the peak power developed by our largest rocket engines. Even when evaluated on the one-second basis, the power is still ten times larger than that developed in the largest turbogenerating unit contemplated today. The state of the art in pulse generation is such, that only the latter requirement can be met by stretching the ambit of the most modern techniques. Achievement of the ultimate goals relies, instead, on the development of completely new schemes employing a technology, that of highly ionized gaseous plasmas, which at the moment is only in its infancy.

In evaluating the feasibility of pulse generation, the most important single parameter is the maximum allowable power density, that is, the peak power output per unit volume of the machine, because this parameter determines the size and cost of the machine. We can derive the power density in an electromechanical power converter of the magnetic type, starting from Ohm's law for a volume element of dense conducting material:

$$\frac{\underset{\sim}{J}}{\gamma} = \underset{\sim}{E}$$

where:

$\underset{\sim}{J}$ = electric current density

$\underset{\sim}{E}$ = electric field intensity

γ = electric conductivity

When stated in this form, the field quantities are measured in a frame of reference attached to the conductor. Since electromechanical power conversion results from the relative motion of the conductors, it is expedient to choose, for reference, a frame which exhibits such motion. When the conductor is seen to be moving with velocity $\underset{\sim}{v}'(\underset{\sim}{v} << c)$, with respect to the frame where the electromagnetic field measures E' and B', Ohm's law transforms into:

$$\frac{\underset{\sim}{J}'}{\gamma} = \underset{\sim}{E}' + \underset{\sim}{v}' \times \underset{\sim}{B}'$$

which, when dotted by $\underset{\sim}{J}'$, yields the following relation between the specific powers per unit volume:

$$\frac{\underset{\sim}{J}'^2}{\gamma} = \underset{\sim}{E}' \cdot \underset{\sim}{J}' + \underset{\sim}{v}' \times \underset{\sim}{B}' \cdot \underset{\sim}{J}'$$

where the term to the left can be identified as the dissipated power and the two terms to the right as the electric and converted power respectively, so that

$$P_{diss} = P_{el} + P_{conv}.$$

In the generating mode of operation:

$$P_{diss} > 0; \; P_{el} < 0; \; P_{conv} > 0;$$

$$\left|P_{el}\right| < \left|P_{conv}\right|$$

$$\frac{\left|P_{el}\right|}{\left|P_{conv}\right|} = \eta \text{ where } \eta \text{ is the conversion efficiency}$$

We observe that, for given magnitude of $\underset{\sim}{v}'$, $\underset{\sim}{B}'$, and $\underset{\sim}{J}'$, the converted power is maximized when these vectors form a perpendicular term. For this case, dropping the primes and expressing J in terms of η, we obtain for the volume density of electric output power

$$P_{el} = \eta(\eta - 1)\,\gamma\, v^2 B^2$$

In the case of solid conductors and using M. K. S. units, we can assume $v = 200 m/sec$ as the maximum allowable velocity. This value actually corresponds to the limit imposed by centrifugal forces in rotating devices, but it is not easily exceeded in devices with linear motion. If we choose for the magnetic flux density the value corresponding to saturation of the iron core, namely $B = 2^{wb}/m^2$ and for the efficiency the matching condition $\eta = 1/2$, we obtain a power output per unit volume of copper conductor ($\gamma = 5 \times 10^7$ mho/m)

$$P_{el} = 2 \times 10^{12} \text{ watt/m}^3$$

This already remarkable figure could be further improved by at least an order of magnitude if and when superconducting magnets will be developed, which perform satisfactorily under transient conditions.

In the case of fluid conductors we can choose as typical, the velocity which is attainable with chemical propellants, that is, 10^4 m/sec. The use of fluid conductors in conjunction with superconducting magnets will bring the output power density to a maximum of 10^{17} watt/m^3. We will discuss later the serious technological problems, which still remain to be solved before highly ionized gases can be used as conductors in electromechanical pulsers, and at this point we shall restrict our consideration to converters employing solid copper as active conducting material. The volume power density allows to calculate the volume of active conductor required for a given output simply as:

$$V = \frac{P_{output}}{P_{el}}$$

With solid conductors, however, this volume does not provide adequate information about the linear dimensions of the device. In fact, thermal and mechanical stresses, combined with the necessity of keeping the reluctance of the magnetic path as low as possible, dictate the requirement that the active conductor be given the shape of a sheet with the smallest dimension in the direction of the magnetic flux density B. Under these conditions it is the surface, rather than the volume, of active conductor which determines the size of the machine and it is, therefore, convenient to introduce another specific power density; the surface power density defined as:

$$P_{s-el} = \underset{\sim}{E} \cdot \underset{\sim}{k} = \eta v B k$$

where $\underset{\sim}{k}$ is the surface current density per unit length in the direction of motion. This power density actually represents the flux of the Poynting vector into a unit area of the active conductor.

The surface current density is limited by thermal stresses in devices designed for continuous operation or long pulses. With short pulses instead, the

limiting factor is, in general, the mechanical stress; in fact the product Bk is a measure of the shear stress on the conductor. Since in the case of solid copper this product should not exceed $10^8 \frac{\text{Newton}}{m^2}$ we obtain for $\eta = \frac{1}{2}$, and v = 200 m/sec a maximum allowable surface power density of the order of:

$$P_{s-el} \doteq 10^{10} \text{ watt/m}^2$$

For a given power output, the surface of active conductor at the gap, where relative motion takes place, is then given by

$$S = \frac{P_{out}}{P_{s-el}}$$

As we shall see the overall dimension of the machine, in the case of continuous output or long pulses are directly related to the surface of active conductor thus obtained.

2. ENDLESS HOMOPOLAR STRUCTURES

The value of the previous relations stems from their generality, since they apply to all kinds of electromechanical converters of the magnetic type. From this point on, however, in order to proceed further in this feasibility study, we need be more specific about the structure considered.

We start with the most symmetrical structure, the endless structure with cylindrical symmetry, where all volume elements of the active conductor are exposed in their motion to a constant value of field intensity. Our interest in this structure ensues from two reasons: first, that the symmetry of the geometry leads to a simple analytical formulation and is, therefore, of great help in clarifying some of the problems involved in pulse generation; secondly, that when the pulse duration is of the order of seconds or more, the endless homopolar device most probably provides the best technical solution. We consider the structure of the homopolar type schematically shown in Fig. 1.

Considering that, in general, two such units are connected back to back along the axis, the surface of active conductor is

$$S = 4\pi \, r_g \, \ell$$

where r_g is the radius at the gap and ℓ is the length of active conductor.

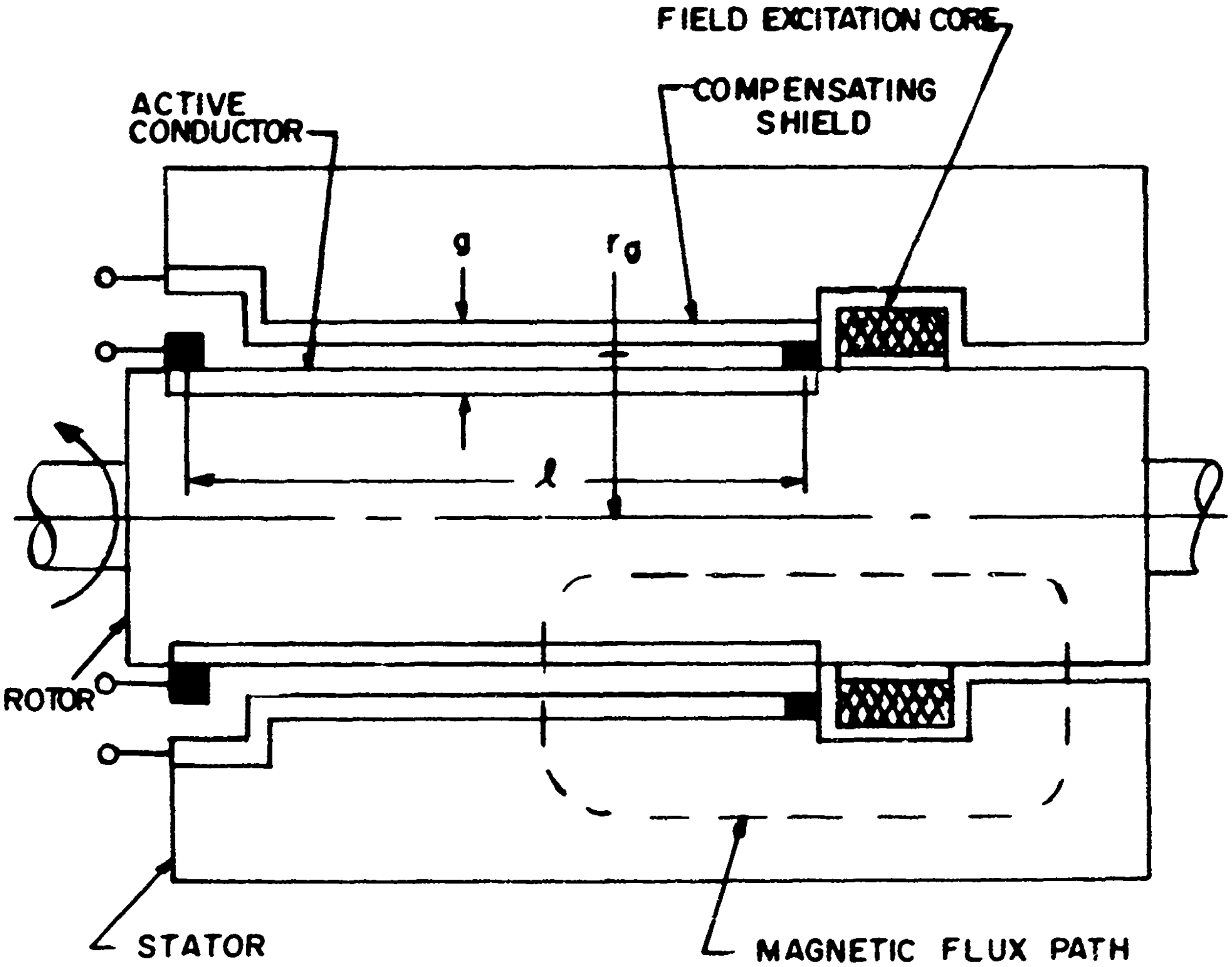

Figure 1. Endless Homopolar Structure.

Since in this structure S also represents the cross section of the magnetic flux-path, continuity of this cross section requires that:

$$\pi r_g^2 = \frac{S}{2} = 2\pi r_g \ell$$

So that

$$\ell = \frac{r_g}{2} = \sqrt{\frac{S}{8\pi}}$$

The overall dimensions of the machine are likewise related to S; if O. D. is the outside diameter,

$$\frac{\pi}{4} \overline{O.D.}^{\,2} = 2\pi r_g^2 = S$$

and if L is the overall machine length,

$$L = 4\ell = 4 \sqrt{\frac{S}{8\pi}}$$

As a result, the overall volume of the machine is:

$$\text{Volume} = \frac{\pi}{4}\,\overline{\text{O.D.}}^{\,2} \times L = \sqrt{\frac{2}{\pi}}\; S^{3/2} = \sqrt{\frac{2}{\pi}}\left(\frac{P_{out}}{P_{s-el}}\right)^{3/2}$$

On the basis of these considerations the volume of the homopolar machine capable of generating the desired pulse energy in one second would be less than $1m^3$. Although the optimum conditions upon which these calculations are predicted may not be attained, the volume thus obtained is quite reasonable and well justifies the pursuit of this investigation.

An obvious reason why the optimum conditions cannot be attained is that with such high energy pulses and low efficiency the thermal stress may become the limiting factor. This is clearly the case here, since, for the assumed 50 percent conversion efficiency, the energy dissipated in the active conductor equals the pulse energy and, as indicated before, is sufficient to melt a volume of steel four times larger than the overall volume of the machine. We recall that 50 percent is the value of efficiency which minimizes the volume of active conductors. If we were to raise the efficiency, for example, up to 90 percent, the volume of conductor would almost triple. This, however, would not necessarily correspond to an increase in the overall volume of the machine, on the contrary, we observe that the specific power per unit surface is proportional to the efficiency so that the increase in efficiency would have only a beneficial effect on the outside dimensions of the machine.

The next question is how we obtain a pulse out of a machine which intrinsically provides only a continuous output? This is a serious problem, but not peculiar to the homopolar machine. Once we have established that, with solid conductors, the limiting factor in pulse generation is the peak power, it is apparent that, for a given pulse energy the shortest duration of the pulse is obtained when the output power rises and decays with time, in a step-like fashion. As a consequence we should always make sure that the time constant of the system is a small fraction of the pulse length. In the case of the homopolar device the pulse output can be controlled without the need of tampering with the output circuit, either by pulsing the velocity, or the field excitation current. If we pulse the velocity, while maintaining constant the field excitation current, the dominant change in energy storage occurs in the inertia of the moving masses. Again it is sufficient to consider only a volume element of active conductor, since in the homopolar device they are all equally stressed.

Referring all quantities to that element, Newton's law can be formulated as:

$$(1 + \zeta)\, \rho \frac{dv}{df} = \underset{\sim}{J} \times \underset{\sim}{B} + \underset{\sim}{f}$$

where ρ is the mass density of active conductor, $\underset{\sim}{f}$ is the external force on a per unit volume basis and ζ is the ratio of external inertia to the inertia of the active conductor.

Combining the expressions for Newton and Ohm's law and taking into account the perpendicular orientation of the relevant vectors, we obtain for the mechanical time constant of the system:

$$\tau_m = \frac{\rho}{B^2} \frac{1}{\gamma} \frac{1 + \zeta}{1 - \eta}$$

where $\frac{\rho}{B^2}$ can be identified as the Alfven equivalent dielectric constant of the active conductor. For copper with

$$\rho = 8.9 \times 10^3 \text{ kg/m3}$$

$$\gamma = 5.10^7 \text{ mho/m}$$

$$\zeta = 10^2$$

$$\eta = 0.9$$

$$B = 2 \text{ Wb/m}^2$$

This time constant is: $\tau = 4.5 \times 10^{-2}$ sec. and, therefore, is barely adequate for pulses of one second duration. Next we examine the possibility of pulsing the field excitation current, while leaving the velocity constant. Under these conditions the machine behaves like an amplifier and, as a consequence, we expect the time constant to be proportional to the power gain

$$G_p = \frac{P_{output}}{P_{excitation}} .$$

If L_f, R_f, i_f, τ_f, represent respectively the inductance resistance, current and time constant of the field excitation circuit, then

$$\tau_f = \frac{L_f}{R_f} = \frac{L_f i_f^2}{R_f i_f^2} = \frac{2 W_{mag}}{P_{excitation}}$$

where W_{mag} is the magnetic energy stored in the gap. If g is the gap length, this energy is:

$$W_{mag} = \frac{1}{2} \int_V \underset{\sim}{H} \cdot \underset{\sim}{B} \, dV = \frac{1}{2} Sg \frac{B^2}{\mu_o}$$

Finally, introducing the power gain G_p and expressing the power output as:

$$P_{out} = Sp_{s-el} = S \eta v B k$$

we obtain:

$$\tau_f = G_p \frac{g}{v} \frac{1}{\eta} \frac{B}{\mu_o k} .$$

For a gain of 10^4, a gap length of 10^{-2} m and the assumed values of the other variables the time constant of the field circuit is found to be:

$$\tau_f = 1.7 \times 10^{-2} \text{ sec.}$$

When the pulse duration is of the order of one second this time constant is quite adequate. It should, however, be pointed out that pulsing the field requires a special construction of the magnetic path which increases the cost of the machine. Similar calculations show that, with a purely resistive load, the time constant of the load circuit is negligible.

Once the homopolar machine has been proved to be capable of delivering the required pulse energy and power, it remains only to determine whether its output voltage is satisfactory. Since the homopolar machine offers only very limited flexibility with respect to impedance matching, we can only hope that the impedance of the load can be designed to match. In the machine considered, the output voltage would be of the order of 100 volt. The prospective of the extremely large output current which ensues is not very encouraging. Alternative solutions, however, are not easily foreseen. The heteropolar machine with rectified output, which is the conventional D-C machine, can indeed produce a higher voltage, by about one order of magnitude. However, such increase in voltage has to be balanced against more than a tenfold reduction in the arc embraced by the current carrying brushes and against the more than tenfold increase in the size of the machine caused by commutation difficulties. There

exists an interesting possibility for raising the output voltage and in effect the output power of a homopolar machine. As proposed by A. K. Das Gupta,[4] the external cylindrical conductor which provides a return path for the load current and screens the iron from the induced magnetic field could be made to rotate in the opposite direction than the inner conductor. Although this type of construction would introduce serious mechanical problems and increase the volume of magnetic energy stored and, therefore, the time constant of the system, its feasibility is well worthwhile investigating.

Evaluation of the time constants which determine the rise and decay time of the pulse has shown that the endless structure does not lend itself to generation of pulses whose duration is much less than one second. In view of this limitation and because of our great interest in shorter pulses we shall consider next the bounded structure, which is best suited for pulses of a few milliseconds or less.

3. BOUNDED STRUCTURES WITH SHIELDED FIELD EXCITATION

Bounded structures are those in which the active conductor in its motion is exposed to the electromagnetic field over a bounded region only. As a consequence the motion induced electric field and currents are time variant and means have to be provided in order to avoid feedback from the pulsed output into the field excitation coil. We consider a structure in which unidirectional coupling, from the D-C to the A-C side only, is ensured by interposing between the excitation and the load circuits a sheet of highly conducting material. This shield effectively freezes in time the desired intensity and profile of the exciting magnetic field distribution. Moreover, in terms of lumped parameters, we find that the effective inductance of the load circuit is drastically reduced as a result of the image currents induced in the field.

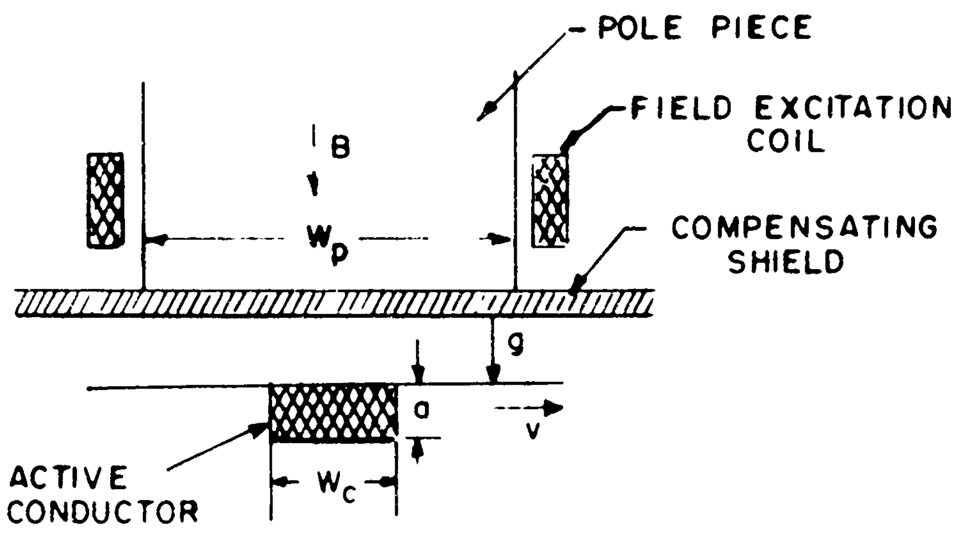

Figure 2. Bounded Structure with Shielded Field Excitation.

In such a structure, the volume and surface of the active conductor are still directly determined by the output power, according to the general relations established in the first section. The overall dimensions of the device, however, are more influenced by the geometry of the pulse in time than by the output power. In fact, by virtue of the Galilean transformation between coordinate systems in relative motion

$$x' = x \pm vt$$

the geometry of the structure, in the direction of motion x, is determined by the specified geometry of the electrical output in time. In particular, the extent of the field region w_p is related to the duration of the pulse T_p as:

$$w_p = v\,T_p \; .$$

Clearly, if we want to keep the power density and therefore the velocity as high as possible, and since it is reasonable to assume that the field region can only span a length of the order of one meter per pole, the pulse duration T_p cannot exceed 5×10^{-3} sec.

We conclude that the maximum pulse energy, per unit surface of active conductor which such a pulser can handle is:

$$w_{el} = P_{s-el}\,T_p = 10^8 \text{ Joule/m}^2 \; .$$

In other words, the bounded structure is limited in the pulse energy it can deliver. Also, unless the load circuit is provided with special switching arrangements, the bounded structure delivers bi-directional pulses at a rigidly predetermined schedule. The great advantage of the bounded structures derives from the fact that the active conductor can be wound to form coils and therefore impedance matching of the electrical output presents no problem. Moreover, the flux distribution can easily be shaped to meet, within close tolerance, the most stringent specifications regarding the pulse geometry and in particular the flatness of the pulse top. The question of pulse shaping, rise and decay times have been the object of intensive study within our group.[5] The major factors involved are the sharpness in definition of the magnetic field region, the width of the active conductor w_c and the time constant of the output circuit. The sharpness of the field boundary is a function of the reluctance at the edge of the magnetic flux path across the gap. Here saturation effects and snapping of the lines of force, due to the variable reluctance, tend to counteract each other, so that, for the purpose of this feasibility study, it is adequate to assume that the magnetic flux density in the gap rises and decays in a step-like fashion. Under these conditions, the elementary strands of the active conductor, which spread over

the width w_c, enter and leave a well defined field region in succession and over a time:

$$T_r = v\, w_c \,.$$

Whether the elementary strands are connected in series, or transposed along the slot in order to avoid eddy currents, the result is that the motion induced voltage cannot rise or decay faster than the time T_r. As a consequence, there exist an upper bound for the allowable width of the active conductor:

$$w_c = \frac{T_r}{v} = \alpha\, w_p$$

where $\alpha = \dfrac{T_r}{T_p}$ is the ratio of rise time to pulse width.

The time constant of the load circuit can be easily calculated since, as it turns out[5, 6] in large pulsers with purely resistive load, most of the magnetic energy is stored in the active conductor itself. If L_L, R_L, i_L represent respectively inductance, resistance and current of the load circuit calculated on a one turn basis, then

$$\tau_L = \frac{L_L}{R_L} = \frac{L_L\, i_L^2}{R_L\, i_L^2} = \frac{2\, W_{mag}}{P_{converted}} = \frac{2 \int_V \underset{\sim}{H} \cdot \underset{\sim}{B}\, dV}{P_{converted}} \,.$$

If we account for the fact that the conductor is imbedded in a material of much higher permeability, the magnetic field within the conductor is directed as $\underset{\sim}{v}$ and its intensity can be expressed as:

$$H = \frac{k}{a}\, y$$

where a is the slot depth and y the distance from the bottom of the slot.

Performing the integration and introducing

$$P_{converted} = \frac{-V_{p_{el}}}{\eta} = w_c \;\; a\, 2\ell\, (1 - \eta)\, \gamma\, v^2\, B^2$$

we obtain:

$$\tau_L = \frac{\mu_o k^2}{3(1-\eta)\gamma v^2 B^2} .$$

We observe that the time constant is an extremely sensitive function of the efficiency, as it should, since the volume of the conductor and therefore the magnetic energy increase rapidly with the efficiency. For the optimum conditions of power output determined in the first section:

$$\tau_L = 2.6 \times 10^{-4} \text{ sec.}$$

and it is quite adequate for the 5 millisecond pulse. We are now in a position to determine the overall dimensions of the machine for a given power output or, in this case, establish the maximum power and energy output that can be obtained from a single unit. The value for τ_L indicates that the time constant of the load circuit is not the limiting factor in the design of the pulser for maximum possible energy output.

The prevailing situation is therefore quite different from the one which has been treated in detail by Pande.[6] For a five millisecond pulse and a rise time of 5×10^{-4} sec. the width of the conductor is of the order of 10^{-1} m. Assuming a single pole pair and a length of active conductor ℓ = 4m, the maximum output energy would be approximately 80 megajoules. Although this energy falls short of the objective by two orders of magnitude it is apparent that the electromechanical pulser with screened excitation does still out-perform a capacitor bank by as much as four orders of magnitude. Moreover, we must realize that all these considerations were based on the output of a single coil. The utilization of the machine volume could be considerably improved and the output energy increased, if a number of coils were placed side by side and the output switched from one coil to another. Although in general realization of such a scheme must wait for a satisfactory solution of the commutation problem, which for the time being is not in sight, it is not excluded that particular types of load could be so energized.

4. PARAMETRIC GENERATION

The rigid tie between the spatial distribution of the impressed magnetic flux, and the geometry of the pulse in time imposes a lower, as well as an upper limit, on the pulse width which is obtainable with shielded structures. At high power this lower limit is of the order of 10^{-4} sec. To overcome this limitation one can remove the shield, which freezes the impressed flux distribution, and allow full reciprocal coupling between the two electrical circuits in relative motion. Since, as we shall see, the resulting converter is of interest as a pulser only when the

conductors are in fluid state, we deliberately refrain from considering a specific structure but we base our study on general energy considerations. The parametric converter of the magnetic type exploits the conservation law for flux interlinkage in order to bring about an exchange between the magnetic energy stored in a conservative system and mechanical work. For simplicity sake we assume that the system can be described in terms of lumped parameters by a single loop carrying the current i_o and storing in the lumped inductance L_o, the magnetic energy:

$$W_o = \frac{1}{2} L_o i_o^2 .$$

If the geometry of the system is subsequently deformed, so that the representative inductance is brought to a new value L_1, the current attains the value

$$i_1 = \frac{L_o i_o}{L_i}$$

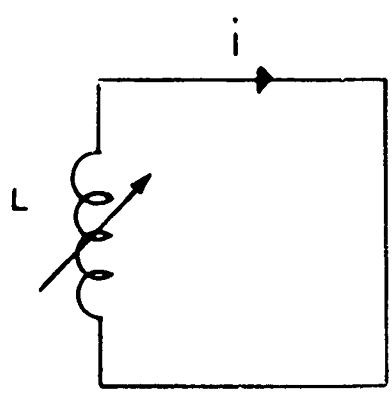

Figure 3. Lumped Parameter Representation of Conservative Parametric Converter.

and the magnetic energy attains the value

$$W_1 = \frac{1}{2} L_1 i_1^2 = W_o \frac{L_o}{L_1} .$$

The change in stored energy

$$W_1 - W_o = \left(\frac{L_o}{L_1}\right) - 1 \ W_o$$

then represents the mechanical work done in deforming the system. Two important conclusions can already be drawn from these relations. One is that the linear dimension of any converter based on these principles must be large. In fact, for economic operation we want the pulse energy and, therefore, the mechanical work to be much larger than the excitation energy, that is:

$$G_e = \frac{W_1 - W_o}{W_o} = \frac{L_o}{L_1} - 1 >> 1.$$

The inductance therefore must undergo a variation of the order of the energy gain. For gains of 10^3 or more this can be realized, only if initially the dimensions of the system exceed a few meters. The second conclusion is that since the current rises in a hyperbolic fashion, the output is sharply peaked and for a given maximum allowable peak power the pulse energy is much lower than in the pulsers previously discussed. It follows that parametric generation in this form is of interest only when the tensile strength does not represent a limiting factor, namely when the conductors are allowed to reach the fluid state. On the other hand, because of their independence from rigid geometrical structures, these pulse generation schemes are probably the only one applicable to fluid conductors and indeed they have been successfully employed in the impulsive generation of high magnetic fields.[7]

So far, we have considered only one of the aspects of the problem: the electromechanical energy conversion. In our terms of reference a pulser must also be capable of transferring this energy into a load. To symbolize this non-conservative process we modify the circuit by introducing a load resistance R_L.

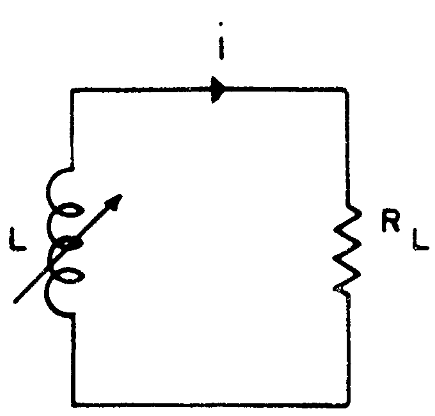

Figure 4. Lumped Parameter Representation of Parametric Pulser.

The current now satisfies the equation:

$$i(t) = \frac{L_o i_o}{L} \left(1 - \frac{1}{\tau_L} \int_o^t \frac{i(t)}{i_o} \, dt\right)$$

where $\tau_L = \frac{L_o}{R_L}$. By expressing the current as a product of two terms in this form, we put in evidence the two competing processing: the collapse of the inductance L which tends to increase the current, and the rate of diffusion of the flux interlinkage which tends to reduce it. For a given electromechanical system, the value of R_L determines whether or not the current increases. It follows that for pulse generation the value of τ_L must be sufficiently large and this again requires large physical dimensions for the converter. An indicative figure is obtained in the limiting case when L vanishes. It has been found[8, 9] that despite the dissipative process the current tends to increase without bound when:

$$\frac{\tau_L}{T} > 1$$

where T is the time required for the inductance to collapse. In a one dimensional structure this relation corresponds to the condition:

$$(1 - \eta) R_m > 1$$

where

$$R_m = \mu_o \gamma v \ell$$

is the magnetic Reynold number and ℓ is the thickness of the active conductor in the direction of v. This again proves that the performance of these devices relies on high values for the velocity which is representative of the deformation of the circuit, and high values for the conductivity of the medium. The latter requirement limits our interest to those fluids whose conductivity is comparable with, or higher than, that of copper, namely, plasmas in the million degree range of temperature. Clearly under these conditions the major problem is that of coupling into the load and the technical solution will be strongly dependent on the type of load. In general, the following three types of coupling can be foreseen:

1) Galvanic coupling pre-supposes that, initially at least, part of the circuit consist of solid conductors and that the major part of the pulse energy be transferred to the load before disruptive instabilities develop.

2) Inductive coupling requires extremely large bearing surfaces to distribute the stresses.

3) Radiative coupling implies conversion of the pulse energy within the plasma into high frequency radiation which is coherent and beamed.

Despite the difficulties involved, the extent of the research effort presently oriented towards these goals gives some hope that the required technology will be developed in a not so distant future.

5. CONCLUDING REMARKS

It has been shown that it is quite feasible, within the realm of present day technology, to generate by electromechanical power conversion, pulse energies of the order of 10^{10} Joules and transfer it to a load in times of the order of one second. The endless homopolar structure is the best suited to generate these relatively long pulses. The rate of energy conversion being the limiting factor it seems unlikely that the delivery time could be reduced by more than one order of magnitude. For pulse widths of the order of milliseconds, the bounded structure with shielded field excitation can be used advantageously to generate, within close tolerances, pulses of a specified geometry in time. The maximum pulse energy that such a unit can generate is of the order of 80 megajoules. Power generation at higher levels must wait for the development of the technology of plasmas in the thermonuclear range of temperature. The major problem then, would be that of coupling into the load.